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# Metaphyseal cones in revision total knee arthroplasty: the role of stems

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# Metaphyseal cones in revision total knee arthroplasty: the role of stems

## **Abstract**

### Objectives:

Metaphyseal titanium cones can be used to manage the tibial bone loss commonly encountered at revision total knee arthroplasty (rTKA). Tibial stems provide additional fixation and are generally used in combination with cones. The aim of this study was to examine the role of the stems to the overall stability of tibial implants when metaphyseal cones are used for rTKA.

### Methods:

This computational study investigates whether stems are required to augment metaphyseal cones at rTKA. Three cemented stem scenarios (no stem, 50mm stem, 100mm stem) were investigated with 10mm deep uncontained posterior and medial tibial defects using 4 loading scenarios designed to mimic activities of daily living (knee bend, standing up, walking, stair descent).

### Results:

Small micromotions (mean 5.6-12 $\mu$ m) were found to occur at the bone-implant interface for all loading cases with or without a stem. Stem inclusion was associated with lower micromotion, however, these reductions were too small to have any clinical significance. Peak interface micromotion even when the cone is used without a stem was too small to effect osteointegration. The maximum difference occurred with stair descent loading where

long stem compared to no stem reduced the implant percentage experiencing 25-40  $\mu\text{m}$  micromotion from 14 to 4%. Stress concentrations in the bone occurred around the inferior aspect of each implant with the largest occurring at the end of the long stem; these may lead to end of stem pain. Stem use is also found to result in stress shielding in the bone along the stem.

#### Conclusions:

When a metaphyseal cone is used at rTKA to manage uncontained posterior or medial defects of up to 10mm depth stem use is not necessary.

#### **Keywords:**

Bone defects; finite element analysis; interfacial micromotion; end of stem pain; von Mises stress

## **Article summary:**

### Article focus:

- Investigate the role of the stem if cones are used at rTKA for two commonly observed bone defects with the joint subjected to four loading scenarios

### Key messages:

- Stem inclusion was associated with lower micromotions, but their magnitude was too small to have any clinical significance
- Stems caused stress concentration at the tip of the stem and stress shielding in the bone along the stem
- The stem is not necessary when a metaphyseal cone is used at rTKA to manage uncontained posterior or medial defects of up to 10mm depth

### Strengths and limitations:

- This is the first study that considers the role of the stem if the metaphyseal cone is used at rTKA
- Time-dependent response of bone is not considered in this study

## Introduction

Bone loss is often encountered at revision total knee arthroplasty (rTKA)<sup>1</sup> and managing large bone deficiencies remains a challenging problem.<sup>2</sup> There is little agreement on the optimal management of bone loss; bone grafts, metal or tantalum augments, metaphyseal sleeves and porous cones have all been advocated.<sup>3</sup> These techniques are generally used in combination with stems which can be short or long and cemented or press-fit.

Biomechanically, tibial stems assist tibial components by sharing loads<sup>4</sup> and reducing tibial implant lift-off and micromotion at the bone-implant interface.<sup>5</sup> Stem use can also assist implant alignment.<sup>6</sup> The potential disadvantages of stems include stress-shielding, peri-prosthetic fracture risk and end-of-stem pain.<sup>4</sup>

Metaphyseal porous cones and sleeves have been designed to replace bone loss at rTKA.<sup>7</sup> In principle, metaphyseal cones and stems have a similar function: to increase the contact area between the tibial bone and the implant thus offloading the complex combination of loads and moments experienced at the interface. The large surface area optimises stresses at the bone-implant interface and the large friction coefficient at the porous coating and bone interface reduces micromotion.<sup>8</sup> A number of clinical<sup>8–11</sup> and experimental<sup>5,7</sup> studies have demonstrated metaphyseal cones to be a viable management solution for bone loss encountered during rTKA.

Where clinical studies have examined cones or sleeves in rTKA, a stem has generally been included as part of the construct<sup>8,12</sup>. However, end-of-stem pain has been reported by a number of clinical studies.<sup>3,13,14</sup> It has been suggested that sleeves or cones could potentially be used without a stem, thereby avoiding both end-of-stem pain and stress shielding.<sup>13</sup> This has been investigated experimentally in a cadaveric tibial model where similar biomechanical conditions in terms of implant stability and surface strain distribution were found when a

cone was used with or without a stem for a single defect type.<sup>5</sup> This computational study considered two different defect locations, four loading scenarios and cones without stems and with two different stem lengths. It also examined stresses around the implants to evaluate the extent of stress shielding caused their presence – this cannot be measured in lab experiments.

This computational study aims to investigate the biomechanical performance of metaphyseal cones used for rTKA with and without stems. Specifically, interface micromotion and cancellous bone stress were examined for two bone loss scenarios (medial and posterior defects) managed using metaphyseal cones both with stems (short and long) and without a stem. Our hypothesis was that the primary stability of the tibial implants is ensured if metaphyseal cones are used for rTKA even without a stem.

## **Methods**

### **Geometry**

A three-dimensional computer-aided design (CAD) model of the tibia was obtained from a previous study.<sup>15</sup> Resection of the tibia model was performed for rTKA; the sectioning plane was a surface perpendicular to the mechanical axis of the tibia, located 8mm below the medial articular surface.

The tibial baseplate was aligned with the central axis of the diaphyseal canal and the baseplate sizing was based on rotation oriented to the medial third of the tubercle and tibial plateau obtaining less than 1mm of overhang. Universal Tibial Baseplate #3 (5521-B-300) was chosen in this study and Triathlon Tritanium Symmetric Cone Augment (Stryker Orthopaedics, Marwah, NJ, USA) Size A (5549-A-110) was considered as per the recommended surgical technique. Three implant constructs were modelled: no stem; short cemented stem (50mm length, 9mm diameter); and long cemented stem (100mm length,

9mm diameter) (Fig. 1a). To avoid any direct contact between the baseplate and the cone, a 2mm thick cement layer was included. Cement was also filled in the medullary cavity up from 175mm depth measured from the sectioning plane to the bottom of the cone.

Uncontained bone defects involving the medial and posterior tibia were considered. Each defect was 10mm deep and commenced 9mm away from the centre of the cone in a posterior or medial direction (Fig 1c and 1d). This resulted in six models for study with two bone defects (posterior and medial) examined for each of the three bone-implant constructs (cone without stem, cone with a short stem and cone with a long stem).

### **Material definition**

The materials were assumed to be homogeneous, isotropic and linear elastic (Table 1).

Poisson's ratio of 0.3 was assumed for all materials.

Fully-bonded interfaces were assumed where the bone or the implant was in contact with cement (i.e. baseplate and cement, cement and cone and cement and bone); frictional contact was assumed at bone-implant interfaces. A standard Coulomb friction coefficient of 0.35<sup>16-19</sup> was employed for baseplate- bone and tritanium cone - bone interfaces, while a coefficient of 1.01<sup>20</sup> was assumed for the tritanium cone coating - bone interface (Fig. 2b).

### **Loading and boundary condition**

The force components  $+F_x$ ,  $+F_y$  and  $+F_z$  act in lateral, anterior and inferior directions and positive moment components were defined accordingly, as shown in Fig. 1. The forces and moments were applied to a reference point which was at the centre of the baseplate and was constrained to the top surface of the baseplate using multi-point constraints. Standard average loads for the knee joint in subjects with 75 kg body weight were chosen from OrthoLoad.<sup>21</sup> Four loading scenarios were selected for the current study: knee bend (squatting), standing



up, walking and descending stairs (denoted as KB, SU, WA and StaD respectively), which cover the majority of the loading conditions encountered during activities of daily living. The time-points with the largest superior-inferior forces ( $F_z$ ) were chosen for WA and KB and the time-points having the largest  $M_x$  were considered for StaD and KB. Forces and moments for all loading scenarios are illustrated in Fig. 2. Similar to previous studies,<sup>22,23</sup> the tibia was truncated and fixed in all degrees of freedom at a distance of 200mm (measured from the sectioning plane Fig. 1c).

### **Output variables**

To evaluate micromotions, corresponding nodes between implants (tibial baseplate and two parts of the cone) and neighbouring bone were paired to produce implant-bone node-pairs by using a customised MATLAB code (MathWorks, US). The micromotions were then evaluated as the displacement at node-pairs due to load application. Five sections along bone were selected to compare the differences in von Mises stresses in the bone for three different combinations of tibial components: cone alone, cone with short stem and cone with long stem. Sections 1 and 2 are located around the cone mid-height and just below the cone respectively. Sections 3 and 4 are located at the tip (distal end) of short and long stems, respectively. The choice of these sections is to determine the stresses around and at the bottom of each of the implant combinations. Section 5 is 50mm away distally from the end of the long stem; all stresses at this section will be carried by the bone and is expected to be similar for all implant combinations.

## **Results**

### **Micromotions:**

The typical micromotion patterns at the bone-implant interface for all four loading scenarios including the mean and 95 percentile micromotions for each model are shown in Fig. 3. In general, it was found that micromotions at the interface were sensitive to the loading scenarios. Walking (WA) and stairs descending (StaD) resulted in higher micromotion compared to knee bend (KB) and standing up (SU). The mean micromotions are generally  $\leq 12.0\mu\text{m}$  for all the models considered in this study (Fig. 3). Micromotions at the interface were grouped in ranges:  $<15\mu\text{m}$ ,  $15\text{-}25\mu\text{m}$  (medium) and  $25\text{-}40\mu\text{m}$  (high). The percentage of surface areas within these ranges relative to total areas of the bone-implant interface were calculated and are shown in Fig. 4 (micromotions  $<15\mu\text{m}$  were excluded).

It was found that micromotions are small for KB and SU (Fig. 3):  $>90\%$  of the area had micromotions  $<15\mu\text{m}$  and they were  $\leq 25\mu\text{m}$  everywhere (Fig. 4a and 4b). A higher range of micromotions was found under WA and StaD loadings scenarios and higher micromotions were observed for bone with an uncontained medial defect compared to an uncontained posterior defect (Fig. 3). The addition of a stem and increasing the length of the stem decreased both medium and high ranges of micromotions (Fig. 4). The mean and 95 percentile micromotions were decreased with the addition of a stem and decreased further with increased stem length (Fig. 3). However, this decrease in micromotion was small. For example, in the medial defect scenario with the StaD loading, the mean micromotion reduced from  $12.0$  (no stem) to  $11.6$  (short stem) and to  $11.2$  (long stem)  $\mu\text{m}$  (Fig. 3). The reductions in average micromotions for bone with a medial defect were only  $3.3\%$  and  $6.7\%$  for short and long stems respectively.

### **Bone stresses:**

The von Mises stresses in the tibial bone along the implant (with and without stems) were evaluated at 5 representative sections for all the loading scenarios considered in this study

(Figs. 5 and 6). Four points at anterior, lateral, medial and posterior locations (A, L, M and P), were selected from each section and the stresses were plotted. It is clear that the variation of stresses at each section is sensitive to the loading scenario (Figs 5 and 6). The percentage differences in von Mises stresses between no stem and short and long stem scenarios under StaD loading are given in Table 2. We examined the bone stresses at different sections:

*Section 1: Located just below the middle of the cone*

When the cone was used without a stem, slightly higher stresses were observed for all loading scenarios, with the exception of the anterior region. Including a stem caused the applied forces and moments to bypass the cone and thus slightly smaller stresses were found, which were further reduced by the increase in stem length. The highest reduction of stresses with a short stem was 11% (for posterior defect) and 26% (for medial defect) in the StaD loading scenario; with the long stem these reductions were 19% and 28% (Table 2).

*Section 2: Bottom of the cone*

The stresses reduced by inclusion of a short stem and reduced further for the long stem. The largest reduction of stress was 24% and 70% for posterior and medial defect scenarios, respectively (Table 2). The highest reduction of stresses was observed in the anterior and lateral regions of the bone for posterior (Fig. 5) and medial (Fig. 6) defect scenarios, respectively, and this is true for all the loading scenarios.

*Section 3: End of the short stem*

Compared to the no stem construct, significantly higher stresses were found at all anatomic locations when a short stem was incorporated for both bone defects considered (Fig. 5 & 6). The stress increment was more than 70% with the short stem compared to cone being used alone (Table 2).

However, long stem use reduced the peri-bone stresses considerably, and these were more than 60% in the anterior region of the bone for both bone defects considered (Table 2).

Essentially this means that a considerable amount of load, or stress, bypassed the cone and was carried by the stem.

#### *Section 4: End of the long stem*

Similarly, for the long stem construct, higher stresses were found at all four locations compared to the short stem and no stem cases, again coincident with the stem tip (Fig. 5 and 6). The elevated stresses found at the end of the long stem were more than 3 times the stresses observed for a cone used alone (Table 2). At this section almost no difference in stresses was found when a cone was used without a stem or with a short stem (Table 2).

#### *Section 5: 50mm away from the end of the long stem*

von Mises stresses were similar for all the implant constructs (i.e. cone with or without stem) with differences of less than 1% (Table 2) for both posterior (Fig. 5) and medial (Fig. 6) defects. This was true for all the loading scenarios considered.

## **Discussion**

Metaphyseal cones are designed to replace large bone defects at rTKA and have been shown to have comparable or superior fixation compared to existing systems in clinical<sup>8-11</sup> and experimental<sup>5,7</sup> studies. A stem is generally considered as additional fixation and is typically used to augment cones. The present study demonstrates that when cones are used to manage uncontained posterior or medial defects in the tibia, compromised primary stability leads to some micromotion at the implant-bone interface and that this occurs with or without a stem. Micromotions at the interface are found to decrease by the inclusion of a stem and decrease further with increasing stem length, however, micromotions are small in all cases with or

without stems. Inclusion of a stem, reduces the stresses in the bone around it and at the bottom of the cone. Stress concentrations occur at the tip of both short and long stems and much larger stress concentrations are found in the tibial bone at the tip of the long stem.

Interfacial micromotion is an important indicator in the evaluation of the mechanical stability of bone-implant constructs. The bone-implant construct experiences large moments during walking and stairs descending (Fig. 2), therefore, these loading scenarios resulted in higher micromotions compared to knee bend and standing up cases. A previous computational investigation for a primary TKA showed that the average micro-movements between cement and bone were reduced by 19% and 23% for press-fit and cemented stems respectively.<sup>1</sup> An experimental study also reported that if the stem is used in combination with a metaphyseal sleeve for rTKA, the micromotion will reduce.<sup>23</sup> The reduction of micromotion at the sleeve region has also been previously reported computationally, however, this reduction was small, around 10% with a stem length of 60mm.<sup>24</sup> In the current study, we found that stem inclusion was associated with lower micromotion. However, the reduction is only 3.3% and 6.7% for short and long stems, respectively, used in conjunction with cones for medial bone defect considered and subjected to descending stairs loading (worst case scenario). This reduction in micromotion is too small for overall tibial construct stability and of doubtful clinical significance. Moreover, micromotions found in this study, for both tibial defects considered, were small in all cases. Previous research has shown that bone ingrowth is achieved if interface micromotions are  $< 50 \mu\text{m}$ .<sup>25,26</sup> The micromotions observed in the current study are far below  $50\mu\text{m}$  for both considered defects using cones with or without stems. Therefore, successful cone osseointegration would be expected even where cones are used without stems for rTKA.<sup>27</sup>

Inclusion of a stem in TKA, primary or revision, may improve mechanical stability but comes at the cost of stress shielding along the length of the stem and has been discussed in a number of studies and reviews.<sup>3,4,9</sup> Computational<sup>24</sup> and experimental<sup>28</sup> studies have reported that the inclusion of stem results in a decrease in proximal tibial strain. The reduction of the strain within the bone (or strain shielding) was observed in a computational study when a stem was used in combination with metaphyseal sleeve for rTKA.<sup>24</sup> A previous experimental study found that tantalum cones produced very similar biomechanical conditions for rTKA with or without a stem by examining the strain distribution at the outer surface of the tibia.<sup>5</sup> However, the strain or stress distribution in the bone at the interface is a better indicator of stability and stress shielding in the bone-implant system. In this computational study, we considered the stress distributions in the bone at the interface. We found that stem inclusion reduced the stresses at the inferior aspect of the cone by up to 29% and 60% for posterior and medial defects respectively. Including a stem and thus offloading the proximal bone defect, therefore, protecting the supported bone may appear desirable. However, the stress shielding at the base of the cone (section 2) and in the bone along the stem is not desirable and may result in bone resorption. Some clinical studies have reported metaphyseal bone resorption after knee reconstructions when a stem is included, suggesting stress shielding.<sup>29,30</sup> Consistent with a previous clinical study,<sup>31</sup> we also observed that the longer the stem, the more proximal bone stress shielding.

The stresses generated within the tibial bone due to bending moments are largely carried by the stem, therefore, the stresses in the bone are reduced at the proximal but elevated at the tip of the stems. The stress concentration at the tip of the stem has been previously reported in experimental and computational studies. An experimental study observed the strain concentration at the stem tip for both cemented and press-fit stem for primary TKA.<sup>28</sup> A computational study reported that the concentrated stress at the tip of the stem up to 4 and 7

times of the stresses of the intact tibia for stem length of 50mm and 100mm respectively.<sup>32</sup>

We too observed stress concentration at the tip of the stem, and the longer the stem the larger the tip stresses. The stresses observed at the tip of the stem here increased up to 77% and 317% for short and long stems, respectively compared to cone used alone for rTKA. Stress concentration at the stem tip can be associated with end of stem pain and potentially put peri-prosthetic bone at risk of fracture,<sup>4</sup> End-of-stem pain is a recognised clinical issue and has been reported by a number of clinical studies.<sup>14,29</sup> Our study shows that inclusion of stems with cones for rTKA does not offer any benefits.

There are a number of limitations of this study. Material nonlinearity was not considered and might influence the strain/strain distributions in the bone.<sup>33–35</sup> Bone properties vary with age and disease and this is not included in the current study. Bone is considered as an isotropic homogeneous material. This assumption simplifies modelling and has been commonly used in almost all previous studies e.g. 15,36,37. This assumption is unlikely to alter the interfacial micromotions and stress trends observed. Bone is known to be a time-dependent material,<sup>38–40</sup> and this time-dependent response accentuates implant loosening when cyclic loading is applied,<sup>41</sup> and the interfacial micromotions are also related to loading frequencies.<sup>42</sup> The biomechanical performances of the bone-implant construct used for rTKA with increased gait cycles need further investigation by the inclusion of the time-dependent response of bone.

This study investigated the role of stems in conjunction with titanium cones in the management of posterior and medial defects at revision total knee arthroplasty. It was found that though stem used in combination with the cone did reduce micromotion at the bone-implant interface, however, these reductions in micromotion were too small to have clinical significance. Peak interface micromotion was small and would not be expected to affect osteointegration even when the cone is used alone without a stem. Although bone stresses

near the defect were reduced by stem inclusion, which may help protect defected bone, undesirable stress-shielding occurs at the base of the cone and in the bone surrounding the stem. Moreover, stress concentrations are observed at the end of the stem, resulting in stresses that are up to three-times those without a stem; these may be associated with end-of-stem pain and peri-prosthetic fracture. Though stemmed tibial components assist in restoring implant alignment, a stemless construct is more bone preserving. Therefore, for the scenarios examined, this computational study shows that when a metaphyseal cone is used for revision total knee arthroplasty, biomechanically the stems may not be necessary. Before stems are abandoned all together, further clinical assessment may help confirm findings of this computational study.

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## References

1. Completo A, Simões JA, Fonseca F, Oliveira M. The influence of different tibial stem designs in load sharing and stability at the cement-bone interface in revision TKA. *Knee*. 2008;15(3):227–32.
2. Mabry TM, Hanssen AD. The Role of Stems and Augments for Bone Loss in Revision Knee Arthroplasty. *J Arthroplasty*. 2007;22(4 SUPPL.):56–60.
3. Vasso M, Beaufils P, Cerciello S, Schiavone Panni A. Bone loss following knee arthroplasty: Potential treatment options. *Arch Orthop Trauma Surg*. 2014;134(4):543–53.
4. Scott CEH, Biant LC. The role of the design of tibial components and stems in knee replacement. *J Bone Joint Surg Br*. 2012;94-B(8):1009–15.
5. Meijer MF, Boerboom AL, Stevens M, Reininga IHF, Janssen DW, Verdonchot N, et al. Tibial component with and without stem extension in a trabecular metal cone construct. *Knee Surgery, Sport Traumatol Arthrosc*. 2017;25(11):3644–52.
6. Dennis DA. A Stepwise Approach to Revision Total Knee Arthroplasty. *J Arthroplasty*. 2007;22(4 SUPPL.):32–8.
7. Faizan A, Bhowmik-Stoker M, Alipit V, Kirk AE, Krebs VE, Harwin SF, et al. Development and Verification of Novel Porous Titanium Metaphyseal Cones for Revision Total Knee Arthroplasty. *J Arthroplasty*. 2017;32(6):1946–53.
8. Derome P, Sternheim A, Backstein D, Malo M. Treatment of Large Bone Defects With Trabecular Metal Cones in Revision Total Knee Arthroplasty. *J Arthroplasty*. 2013;29(1):122–6.
9. Lachiewicz PF, Bolognesi MP, Henderson RA, Soileau ES, Vail TP. Can tantalum cones provide fixation in complex revision knee arthroplasty? *Clin Orthop Relat Res*. 2012;470(1):199–204.
10. Denehy K, Abhari S, Krebs VE, Higuera-Rueda CA, Samuel LT, Sultan AA, et al. Excellent Metaphyseal Fixation Using Highly Porous Cones in Revision Total Knee Arthroplasty. *J Arthroplasty*. 2019;
11. Rao BM, Kamal TT, Vafaye J, Moss M. Tantalum cones for major osteolysis in revision knee replacement. *Bone Jt J*. 2013;95 B(8):1069–74.
12. Lachiewicz PF, Watters TS. Porous metal metaphyseal cones for severe bone loss: When only metal will do. *Bone Jt J*. 2014;96B(11):118–21.
13. Gøttsche D, Lind T, Christiansen T, Schrøder HM. Cementless metaphyseal sleeves without stem in revision total knee arthroplasty. *Arch Orthop Trauma Surg*. 2016;136(12):1761–6.
14. Barrack RL, Rorabeck C, Burt M, Sawhney J. Pain at the End of the Stem After Revision Total Knee Arthroplasty. *Clin Orthop Relat Res*. 1999;(367):216–25.

15. Scott CEH, Eaton MJ, Nutton RW, Wade FA, Evans SL, Pankaj P. Metal-backed versus all-polyethylene unicompartmental knee arthroplasty. *Bone Joint Res.* 2017 Jan;6(1):22–30.
16. Abdul-Kadir MR, Hansen U, Klabunde R, Lucas D, Amis A. Finite element modelling of primary hip stem stability: The effect of interference fit. *J Biomech.* 2008;41(3):587–94.
17. Kuiper JH, Huiskes R. Friction and stem stiffness affect dynamic interface motion in total hip replacement. *J Orthop Res.* 1996;14(1):36–43.
18. Rancourt D, Shirazi-Adl A, Drouin G, Paiement G. Friction properties of the interface between porous-surfaced metals and tibial cancellous bone. *J Biomed Mater Res.* 1990;24(11):1503–19.
19. Viceconti M, Muccini R, Bernakiewicz M, Baleani M, Cristofolini L. Large-sliding contact elements accurately predict levels of bone-implant micromotion relevant to osseointegration. *J Biomech.* 2000;33(12):1611–8.
20. Frank RM, Fabi D, Levine BR. Modern porous coatings in orthopaedic applications. In: *Thin Films and Coatings in Biology*. Springer; 2013. p. 69–103.
21. Bergmann G, Bender A, Graichen F, Dymke J, Rohlmann A, Trepczynski A, et al. Standardized loads acting in knee implants. *PLoS One.* 2014;9(1).
22. Completo A, Fonseca F, Simões JA. Finite Element and Experimental Cortex Strains of the Intact and Implanted Tibia. *J Biomech Eng.* 2007;129(5):791.
23. Nadorf J, Kinkel S, Gantz S, Jakubowitz E, Kretzer JP. Tibial revision knee arthroplasty with metaphyseal sleeves: The effect of stems on implant fixation and bone flexibility. *PLoS One.* 2017/05/10. 2017;12(5):1–20.
24. Awadalla M, Al-Dirini RMA, O'Rourke D, Solomon LB, Heldreth M, Rullkoetter P, et al. Influence of Stems and Metaphyseal Sleeve on Primary Stability of Cementless Revision Tibial Trays Used to Reconstruct AORI IIB Defects. *J Orthop Res.* 2019;37(7):1033–41.
25. Taylor M, Barrett DS, Deffenbaugh D. Influence of loading and activity on the primary stability of cementless tibial trays. *J Orthop Res.* 2012;30(9):1362–8.
26. Taylor M, Prendergast PJ. Four decades of finite element analysis of orthopaedic devices: Where are we now and what are the opportunities? *J Biomech.* 2015;48:767–78.
27. Bourne RB, Finlay JB. The influence of tibial component intramedullary stems and implant-cortex contact on the strain distribution of the proximal tibia following total knee arthroplasty: An in vitro study. *Clin Orthop Relat Res.* 1986;(208):95–9.
28. Completo A, Fonseca F, Simões JA. Strain shielding in proximal tibia of stemmed knee prosthesis: Experimental study. *J Biomech.* 2008;41(3):560–6.
29. Bugler KE, Maheshwari R, Ahmed I, Brenkel IJ, Walmsley PJ. Metaphyseal Sleeves

- for Revision Total Knee Arthroplasty: Good Short-Term Outcomes. *J Arthroplasty*. 2015;30(11):1990–4.
30. Martin-Hernandez C, Floria-Arnal LJ, Muniesa-Herrero MP, Espallargas-Doñate T, Blanco-Llorca JA, Guillen-Soriano M, et al. Mid-term results for metaphyseal sleeves in revision knee surgery. *Knee Surgery, Sport Traumatol Arthrosc*. 2017;25(12):3779–85.
  31. Gustke K. Optimal use of stems in revision TKA. *Semin Arthroplasty*. 2018;29(3):260–4.
  32. Completo A, Talaia P, Fonseca F, Simões JA. Relationship of design features of stemmed tibial knee prosthesis with stress shielding and end-of-stem pain. *Mater Des*. 2009;30(4):1391–7.
  33. Donaldson FEE, Pankaj P, Simpson AH. Bone properties affect loosening of half-pin external fixators at the pin – bone interface. *Injury*. 2012;43(10):1764–70.
  34. Pankaj P, Xie S. The risk of loosening of extramedullary fracture fixation devices. *Injury*. 2019;50:S66–72.
  35. Pankaj P. Patient-specific modelling of bone and bone-implant systems: the challenges. *Int J Numer Meth Bio*. 2013;29:233–49.
  36. Danese I, Pankaj P, Scott CEH. The effect of malalignment on proximal tibial strain in fixed-bearing unicompartmental knee arthroplasty. *Bone Jt Res*. 2019;8(2):55–64.
  37. Conlisk N, Howie CR, Pankaj P. Quantification of interfacial motions following primary and revision total knee arthroplasty: A verification study versus experimental data. *J Orthop Res*. 2017;1–10.
  38. Xie S, Manda K, Wallace RJ, Levrero-Florencio F, Simpson AHRW, Pankaj P. Time Dependent Behaviour of Trabecular Bone at Multiple Load Levels. *Ann Biomed Eng*. 2017;45(5):1219–26.
  39. Manda K, Xie S, Wallace RJ, Levrero-Florencio F, Pankaj P. Linear viscoelasticity - bone volume fraction relationships of bovine trabecular bone. *Biomech Model Mechanobiol*. 2016;15(6):1631–40.
  40. Manda K, Wallace RJ, Xie S, Levrero-Florencio F, Pankaj P. Nonlinear viscoelastic characterization of bovine trabecular bone. *Biomech Model Mechanobiol*. 2016;16:173–89.
  41. Xie S, Manda K, Pankaj P. Time-dependent behaviour of bone accentuates loosening in the fixation of fractures using bone-screw systems. *Bone Joint Res*. 2018;7(10):580–6.
  42. Xie S, Manda K, Pankaj P. Effect of loading frequency on deformations at the bone–implant interface. *Proc Inst Mech Eng Part H J Eng Med*. 2019;095441191987797.
  43. Stryker. Engineered for bone [Internet]. 2017. Available from: [https://www.stryker.com/builttofuse/media/assets/3434TriC\\_TechSummaryTRICC-](https://www.stryker.com/builttofuse/media/assets/3434TriC_TechSummaryTRICC-)

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**Table 1 Material properties used**

Parts	Young's modulus E(MPa)	Poisson's ratio $\nu$
Cortical bone <sup>33</sup>	15,250	0.3
Trabecular bone	449	
Tibial baseplate	210,000	
Bone cement <sup>1</sup>	2,280	
Stem	117,000	
Titanium cone <sup>43</sup>	117,000	
Tritanium cone coating <sup>43</sup>	6,200	

**Table 2 von Mises stresses of bone at five representative sections for the three implant constructs under the loading scenario stair descent. For comparison, the stresses displayed when a short or long stem was added are represented as percentage differences compared to no stem**

		Posterior defect				Medial defect			
		Anatomic location	No Stem (Mpa)	Stress difference to NO stem (%)		No Stem (Mpa)	Stress difference to NO stem (%)		
				Short Stem	Long Stem		Short Stem	Long Stem	
Cone	Section 1	A	0.34	-1%	4%	0.26	-4%	-12%	
		M	1.82	-11%	-24%	3.00	-14%	-29%	
		P	1.70	-11%	-16%	3.67	-13%	-19%	
		L	0.73	-10%	-19%	0.31	-26%	-28%	
Short stem tip	Section 2	A	0.86	-29%	-24%	0.83	-24%	6%	
		M	0.93	15%	20%	1.51	36%	3%	
		P	1.36	-22%	-8%	1.15	-43%	-11%	
		L	0.64	-16%	-5%	0.55	-60%	-70%	
Long stem tip	Section 3	A	0.23	46%	-63%	0.23	50%	-64%	
		M	0.41	43%	-38%	0.44	63%	-26%	
		P	0.57	52%	-38%	0.59	58%	-37%	
		L	0.29	70%	-47%	0.38	77%	-47%	
	Section 4	A	0.28	-3%	31%	0.27	0%	44%	
		M	0.49	1%	105%	0.50	1%	113%	
		P	0.68	1%	113%	0.68	1%	120%	
		L	0.28	0%	306%	0.28	-1%	317%	
	Section 5	A	0.18	-1%	-3%	0.18	-2%	-4%	
		M	0.63	-1%	0%	0.63	0%	0%	
		P	0.99	0%	0%	0.99	0%	0%	
		L	0.44	1%	2%	0.42	5%	6%	

Note: Negative and positive differences simply imply that the stresses observed in the bone are smaller or larger, respectively, than those found for the cone used without a stem.

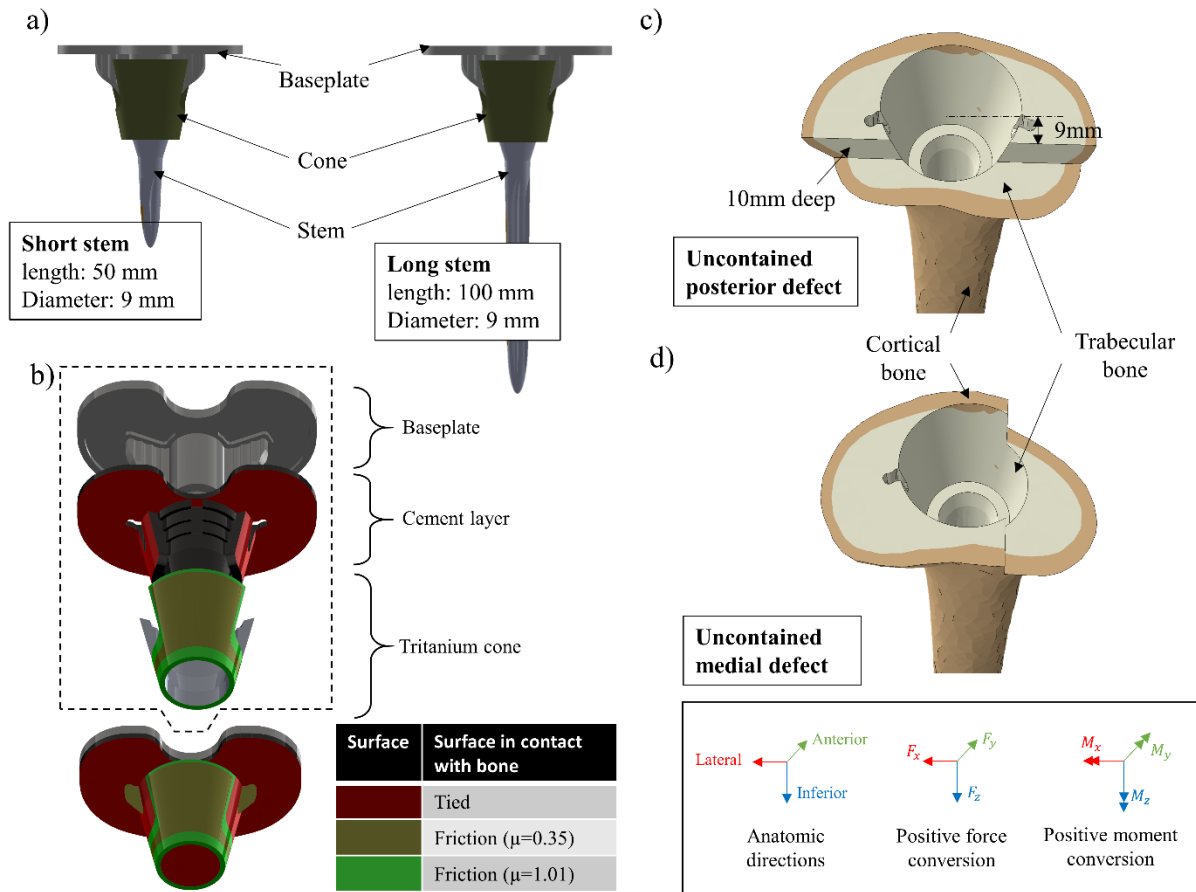


Figure 1: Illustration of two stems considered: short or long stems (a); the setup of metaphyseal tritanium cone together with illustration of contact properties (b); uncontained posterior (c) and medial (d) defects. The positive axes point to lateral, anterior and inferior directions for  $F_x$ ,  $F_y$  and  $F_z$  respectively, and for positive moments are defined accordingly

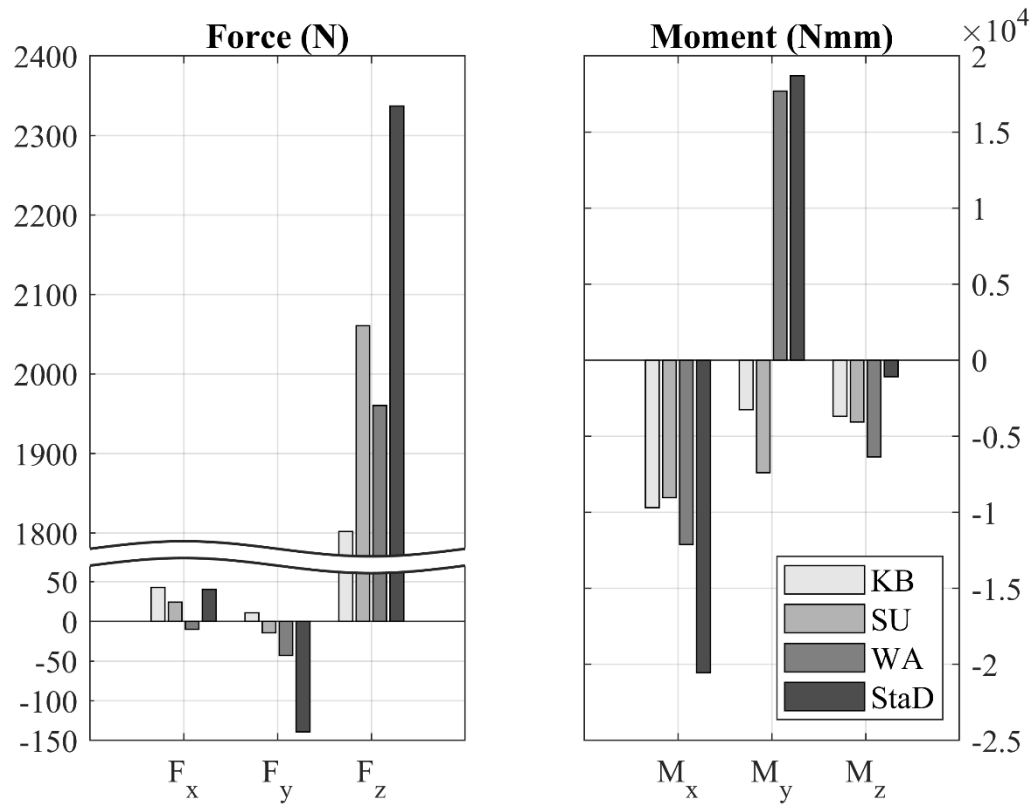


Figure 2: Loadings applied. Six degrees of freedom were considered for load application, three forces and three moments. Four loading scenarios were considered: knee bend or squatting (KB) standing up (SU), walking (WA) and descending stairs (StaD)



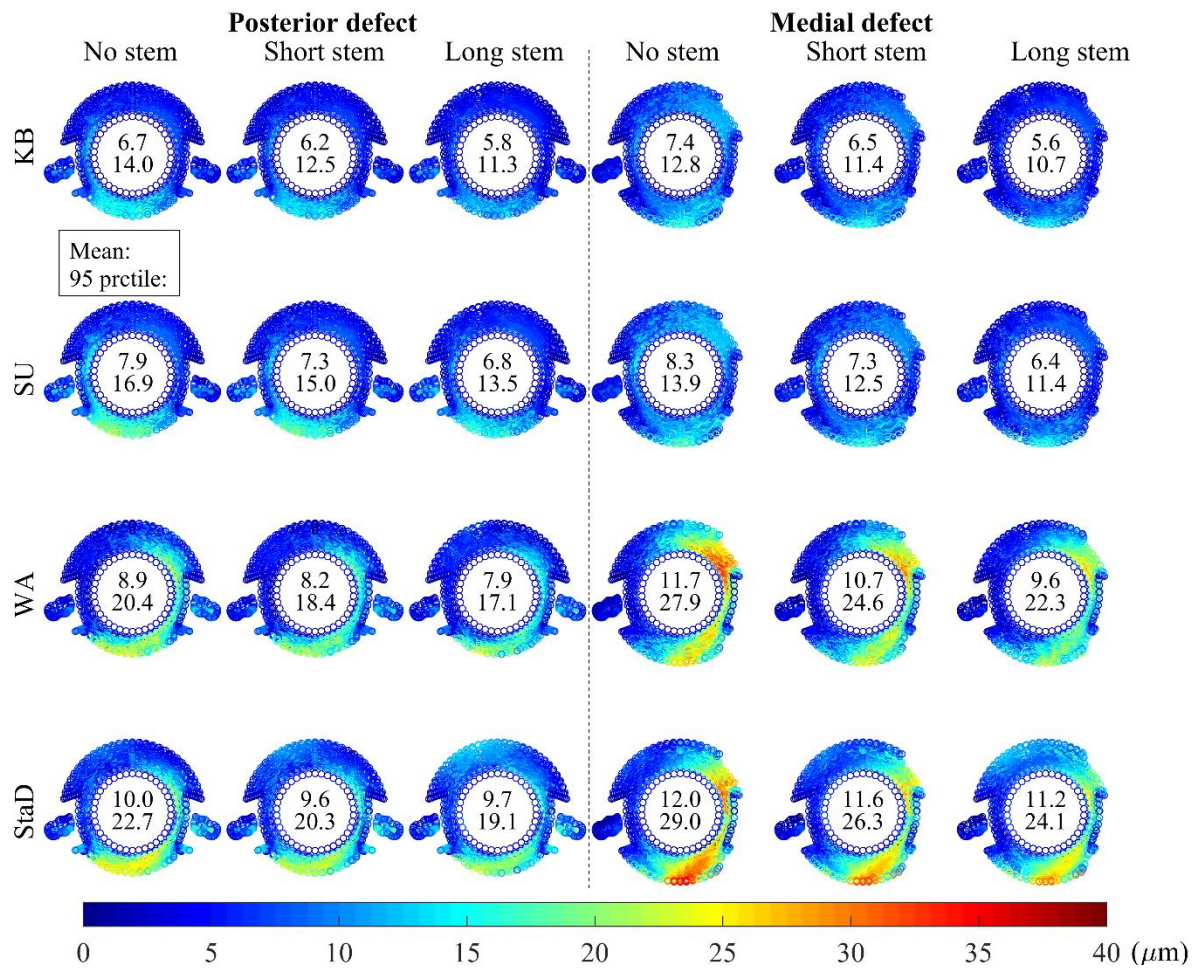


Figure 3: Superior view of micromotion contours at the bone-implant interface for all loading scenarios for the two bone defects considered. The mean and 95 percentile of micromotions for each model are also shown.

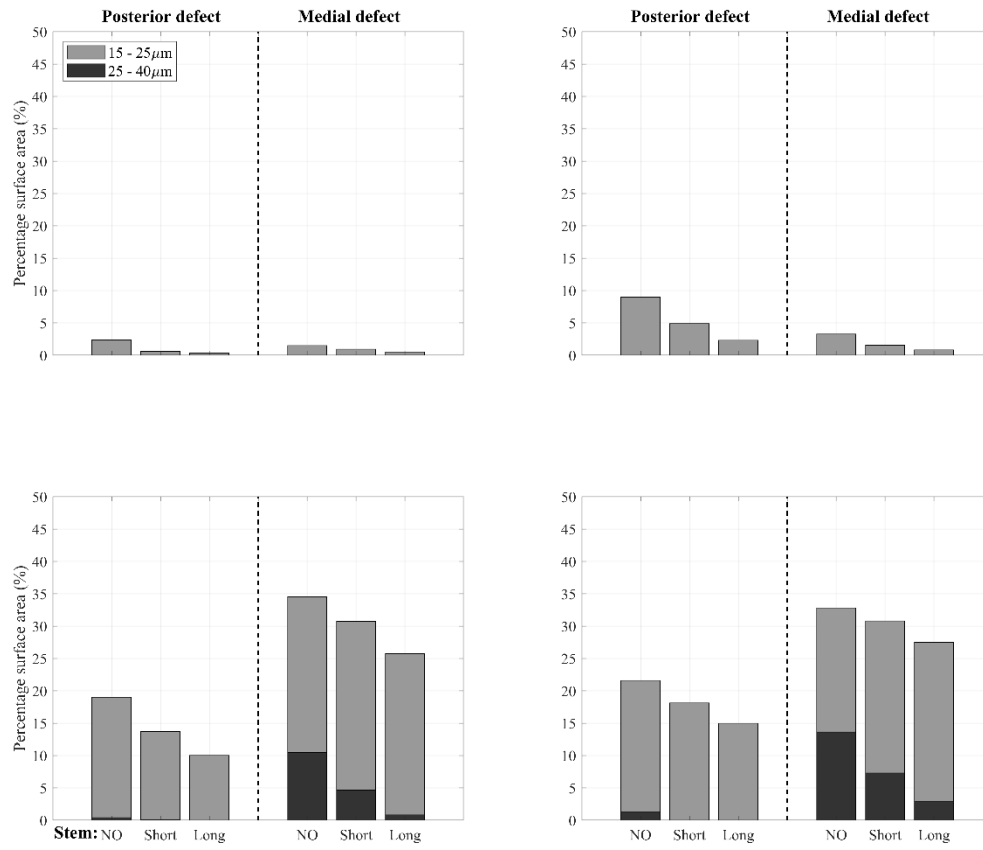


Figure 4: Comparison of the predicted micromotions occurring at the bone-implant interface by range for: knee bend (a); standing up (b); walking (c); descending stairs (d);

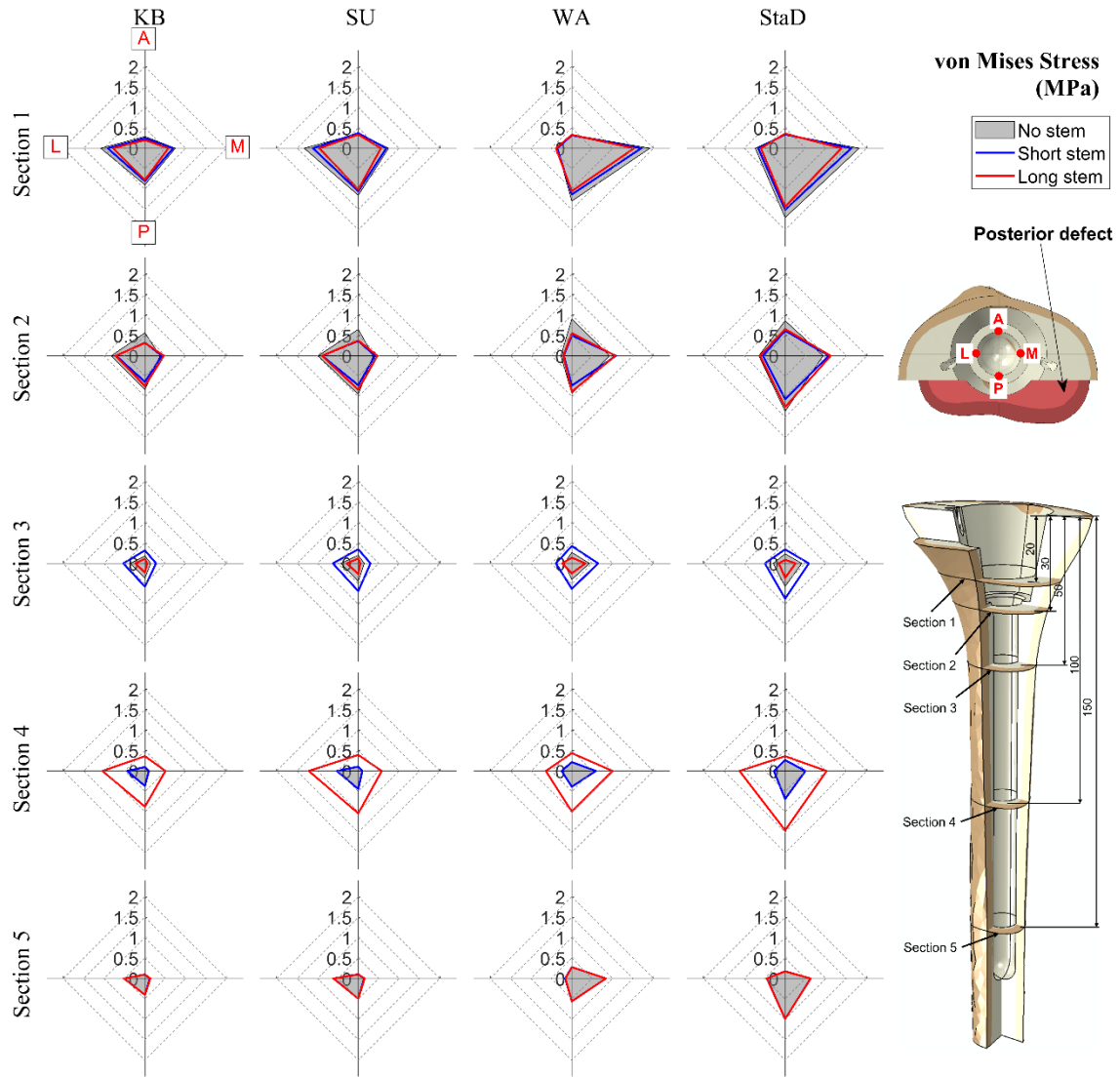


Figure 5: von Mises stress of posterior defected bone from four anatomic points (anterior: A, lateral: L, medial: M and posterior: P) when the cone was used for revision total knee arthroplasty without stem, with a short stem or a long stem. Four loading scenarios were considered: knee bend (KB), standing up (SU), walking (WA) and stairs descending (StaD)

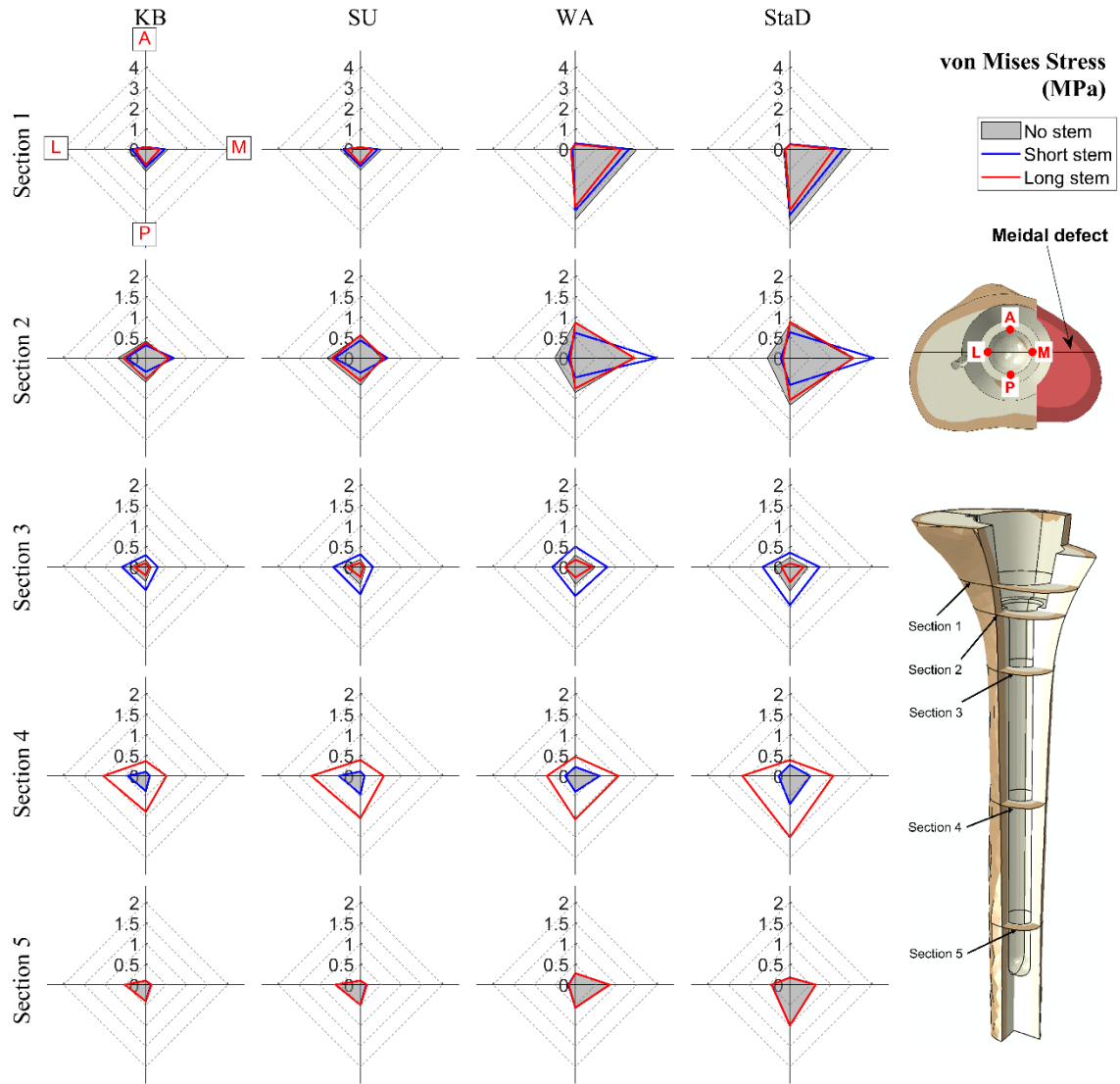


Figure 6: von Mises stress of medial defected bone from four anatomic points (anterior: A, lateral: L, medial: M and posterior: P) when the cone was used for revision total knee arthroplasty without stem, with a short stem or a long stem. Four loading scenarios were considered: knee bend (KB), standing up (SU), walking (WA) and stairs descending (StaD)